Micromachined 5-axis Motion Sensor
with Electrostatic Drive and Capacitive Detection

Nobumitsu Taniguchi*, Kazuhiro Okada*
Yoshiyuki Watanabe, Toshiaki Mitsui**, Takashi Mineta**, Seiya Kobayashi****
*** WACOH Corporation (http://www.wacoh.co.jp)**
Tsuzuki Bldg. 4F, 4-244-1 Sakuragi-cho, Omiya-shi, Saitama Japan
TEL +81-48-641-9995, FAX +81-48-641-9996 e-mail:taniguchi@wacoh.co.jp
****Yamagata Research Institute of Technology**
2-2-1 Matsuei, Yamagata, 990-2473, JAPAN

Abstract

We have succeeded to measure 5-axis motion independently with one unit of sensor chip, which is made by silicon bulk-micromachining technology. The 5-axis motion is composed of 3-axis acceleration and 2-axis angular rate. This sensor has a seismic mass, which is attached on a thin silicon beam and vibrated along Z-axis. By acceleration, Newton's force Fx, Fy and Fz act on the mass (F = mA , **m**: mass, **A**: acceleration). And by angular rate around X and Y-axis, the Coriolis force Fcy, and Fcx also act on the mass (Fc = 2mΩVz, Ω**:** angular rate, **Vz**: velocity of the mass along the Z-axis). Through detecting the position of the mass, we measure 5-axis motion. To vibrate the mass, we adopt the electrostatic force, and to measure the position of the mass, we used a change of electrostatic capacitance.

Keywords: angular rate, acceleration, silicon micromachining, 2-axis, 3-axis, 5-axis

1 INTRODUCTION

To detect the movement of an object, the way of measuring the multi-axis acceleration and multi-axis angular rate is practically used in the various fields. Actually, numerous accelerometers and angular rate sensors are used in this purpose, for example, air bag system, chassis control system, video camcorder and controller for computer game. And the number of the sensor and the application fields will increase in prospect.

Although the movement is originally vector quantity, most of sensors are so-called uni-axial sensor, which detect only one axial direction. So we have to use a few accelerometers and a few angular rate sensors. Therefore multi-axis motion sensor is eagerly required to minimize the size and cost of the system.

The 3-axis accelerometer [1,2,3,4] and the 2-axis angular rate sensor [5] are developed. Through these experiences we already presented 5-axis motion sensor to confirm the basic theory of this sensor system [6]. Basic structure of the sensor is established at the thesis [6]. At the former sensor, we used electromagnetic coil to vibrate the mass. So the size of the sensor was not small enough, and fabrication was difficult.

This paper describes new type of 5-axis motion sensor made by silicon bulk-micromachining technique. This time we adopt the electrostatic force to vibrate the mass. Consequently, we have succeeded to minimize the size and fabrication cost of the sensor.

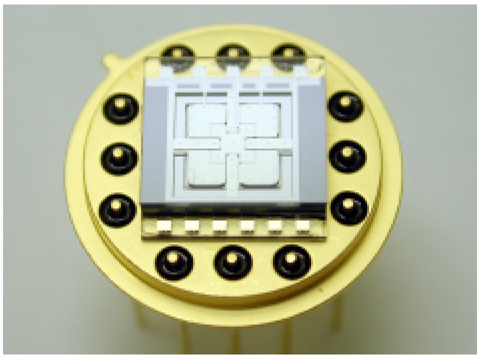


Fig.1: The 5-axis motion sensor

2 STRUCTURE

As shown in Fig.2, this 5-axis motion sensor consists of glass1-silicon1-silicon2-glass2 layer. In the silicon1 layer, 4 beams (length: 2.2mm width: 0.4mm thickness: 0.04mm) and 4 sensing plates are formed and connected each other at the center of the layer, and the other ends of the beams are attached to a frame which is formed surrounded the silicon1layer.

The seismic mass is formed in silicon2 layer, and is suspended by 4 beams at the center of the mass.

At the galass1 layer, 7.5μm gap and sensing electrodes (X+, X-, Y+, Y-, Sz) are formed, and at the glass2 layer, 7.5μm gap and driving electrodes (D1-D4, Dz) are also formed on the surface of the glass.

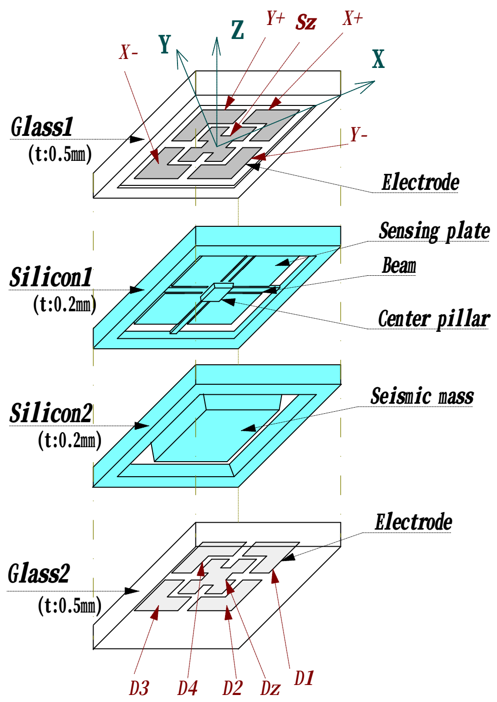
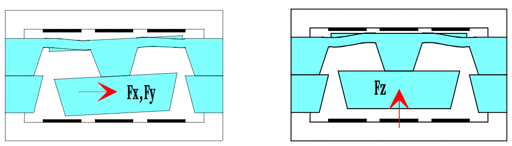


Fig.2: Structure of the sensor

3 PRINCIPLE

When a force acts on the mass, which is suspended by beams, the position of the mass is changed along the direction of the force. By the force of X or Y-axis direction, the position of the mass changed as shown in fig.3(a), and by the force of Z-axis direction, the mass is displaced as shown in fig.3(b). At the same time, the distance between the 4 sensing plates and 4 electrodes is changed. So measuring the electrostatic capacitance between the 4 sensing plates and 4 electrodes, the force works on the mass can be measured.



(a) X(Y)-axis force (b) Z-axis force

Fig. 3: Displacement of the seismic mass

3.1 2-axis Angular rate

By the supplement of sign wave voltage to the electrodes (D1-D4), the mass vibrates along the Z-axis.

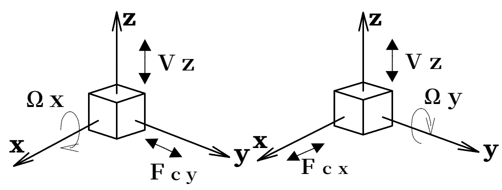
Under the conditions, when the mass is rotated around the X-axis, the Coriolis force is generated along the Y-axis direction, as fig.4(a). And when the mass is rotated around the Y-axis, the Coriolis force is generated along the X-axis direction, as fig.4(b)

X and Y-axis Coriolis force are described in equations (1) and (2) where Fcx and Fcy are Coriolis force, m is weight of the mass, Ωy and Ωx are input angular rate to be measured, and Vz is velocity of Z-axis vibration.

$$Fcx = 2\,m\,\Omega y\,Vz \quad (1)$$

$$Fcy = 2\,m\,\Omega x\,Vz \quad (2)$$

As shown in fig.5, the signal of X or Y-axis direction and reference signal, which is synchronized Vz, are input to the synchronous detector. And though amplifier and filter, the angular rate can be measured.



(a) X-axis rotation (b) Y-axis rotation

Fig.4: Principal of 2-axis angular rate sensor

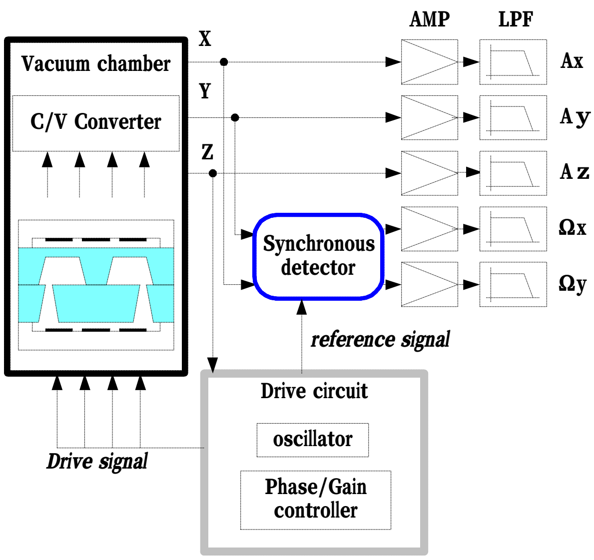


Fig.5: Block diagram

3.2 3-axis acceleration

By acceleration, Newton's force Fx, Fy and Fz act on the mass and change the position of the mass. By change of electrostatic capacitance, the acceleration can be measured. [1,2,3,4] And the equations is as (3).

$$Fx\ (y,z) = m\ Ax\ (y,z) \qquad (3)$$

But the mass is vibrating along the Z-axis. Therefore the vibration signal is overlapped in the Z-axis direction's acceleration signal. And in the X- and Y-axis direction's acceleration signal, the signal of Coriolis force is overlapped. The acceleration to be measured is ranged from DC to 30Hz. On the other hand, the frequency of these unexpected signals is almost as same as vibration frequency. Therefore using the low pass filter, as shown in Fig.5 acceleration can be separated.

4 FABRICATION

The fabrication process sequence is shown in Fig.6.

(a) A silicon wafer (Silicon1) was anisotropically wet etched through with TMAH solution from both sides to form the beams, sensing plates and center pillar.

(b) A silicon wafer (Silicon2) was fusion bonded to the silicon1 at 1100℃ in nitrogen atmosphere.

(c) After thermal oxidation, the mass was released from the frame by anisotropic wet etching.

(d) Two glass wafers that have the gap of 7.5μm and Pt/Cr fixed electrodes were anodically bonded to the both sides of the Si-Si structure. Finally, grooves for chip-break lines were diced, and the wafers were separated to sensor chips.

The chip size of the sensor is 8.4mm×8.0mm×1.4mm.

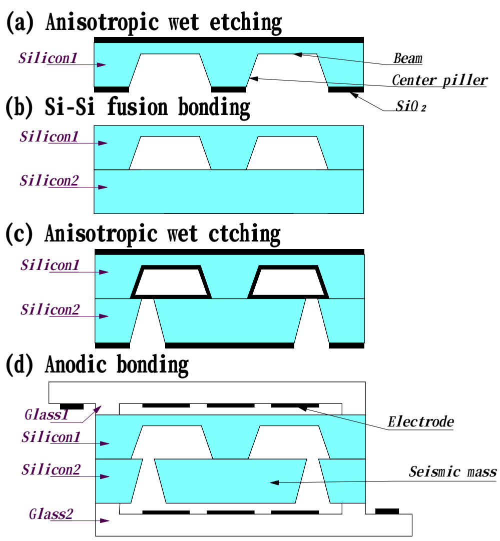


Fig.6: Fabrication process

5 RESULT

5.1 Frequency characteristics of each axis

The frequency characteristics of this sensor are as shown in Fig.7. The resonant frequency of X- and Y-axis are 2030Hz and 2040Hz shown as Fig.7(b). And the resonant frequency of Z-axis is 1880Hz as Fig.7(a). Because the structure of the sensor is symmetric with respect to the X- and Y-axis, the resonant frequency of these two axis are very close.

This time we vibrate the mass along Z-axis at 1875Hz, which is close to resonant frequency of Z-axis, using the way of applying 4Vpp sine wave with 4V offset voltage to the electrodes D1-D4.

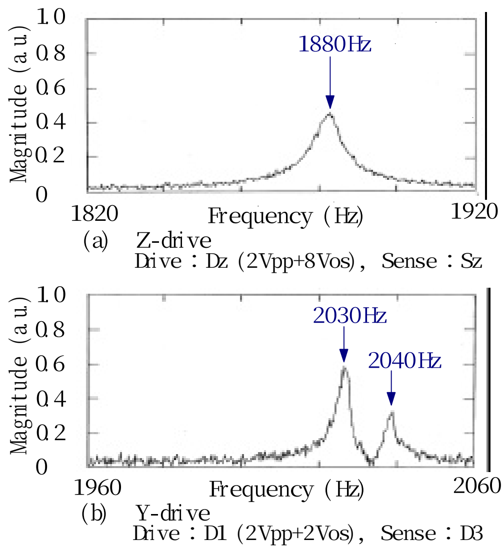
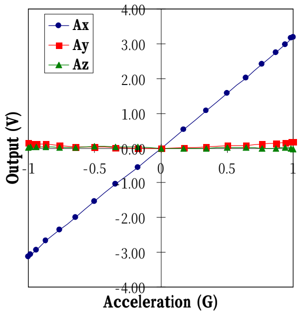


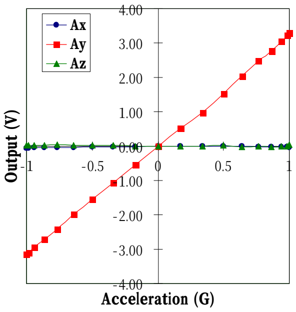
Fig.7: Frequency characteristics

5.2 3-axis acceleration

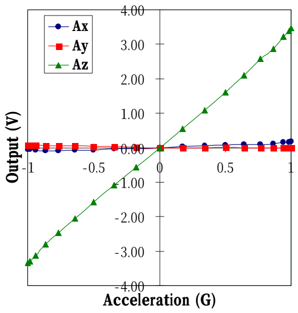
Acceleration characteristics were measured using gravitation of earth by rotating along each axis. During the measurement, the mass is vibrated along Z-axis. Results of 3-axis acceleration test are shown in Fig.8. The sensitivities of Ax, Ay, Az acceleration were 3.23V/G, 3.12V/G and 3.40V/G, which were equivalent to 5.9fF/G, 5.7fF/G and 23fF/G, respectively. The cross-axis sensitivity was approximately 5%. These results were similar to the non-driven measurement results.



(A) X-Axis Acceleration

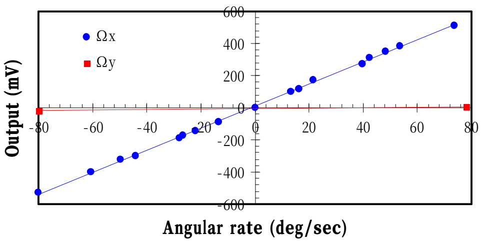


(B) Y-Axis Acceleration

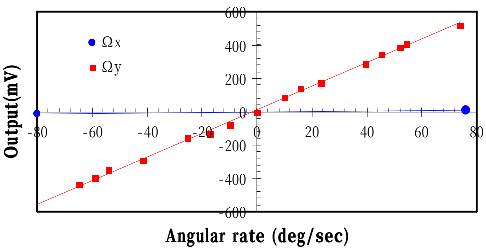


(C) Z-Axis Acceleration

Fig. 8: Acceleration characteristics



(a) Angular rate around X-axis (Ωx)



(b) Angular rate around Y-axis (Ωy)

Fig .9: Angular rate characteristics

5.3 2-axis angular rate

Measured characteristics of angular rates around X and Y-axis are shown in Fig.9. The sensitivity of Ωx and Ωy were 6.8mV/[deg/s] and 7.0mV/[deg/s], which were equivalent to 2.7aF/[deg/s], 2.8aF/[deg/s], respectively. The cross-axis sensitivity of Ωx against Ωy were less than 3%. The cross-axis sensitivity of Ωz against Ωx and Ωy was almost 0%.

6 CONCLUSION

We have succeeded to develop the 5-axis motion sensor, which can be measured 3-axis acceleration and 2-axis angular rate independently with one unit of sensor chip.

Measured sensitivities of accelerations are approximately 23fF/G in Az, and approximately 6fF/G in Ax and Ay. The cross-axis sensitivity was approximately 5%. The sensitivities of angular rates are 3aF/[deg/s] in Ωx and Ωy at an electrostatic resonant drive of 1875Hz. The cross-axis sensitivity was less than 3%. The chip size of developed sensor is 8.4mm×8.0mm×1.4mm.

7 References

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